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LCA FOR AGRICULTURE

Comparative life cycle assessment of rapeseed oil and palm oil

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Abstract

Background, aim and scope The environmental effect of globalisation has been debated intensively in the last decades. Only few well-documented analyses of global versus local product alternatives exist, whilst recommendations on buying local are vast. At the same time, the European Environmental Agency's Third Assessment concludes that the resource use within the EU is stabilising at the expense of increased resource use for import of products to the EU. Taking its point of departure in vegetable oils, this article compares rapeseed oil and palm oil as a local and a global alternative for meeting the increasing demand for these products in the EU. By using detailed life cycle assessment (LCA), this study compares the environmental impacts and identifies alternative ways of producing rapeseed oil and palm oil to the EU market in order to reduce environmental impacts.

Materials and methods The consequential approach for system delimitation is applied (Ekvall and Weidema 2004; Weidema 2003; Schmidt 2008a; Schmidt and Weidema 2008). This approach differs from the attributional approach in a way that the actual affected suppliers and technologies are modelled instead of averages. In addition, co-product allocation is avoided by system expansion. The method for life cycle impact assessment (LCIA) is EDIP97 updated (LCA-Center 2007). In addition, land use and the associated impacts on biodiversity are assessed using the LCIA method described in Schmidt (2008b).

Results The characterised results of the LCA show that palm oil is environmentally preferable to rapeseed oil within ozone depletion, acidification, eutrophication, photochemical smog and land use, whilst the differences within global warming and biodiversity are less clear. The most significant process contributing to global warming from rapeseed oil is the cultivation of rapeseed, whilst the oil palm cultivation and the palm oil mill (effluent treatment) are equally important. Regarding land use and biodiversity for rapeseed oil, the avoided production caused by system expansion has a major role, whilst system expansion has only limited effect on the results of palm oil.

Discussion Alternative cultivation practices and technologies are assessed. The findings for rapeseed oil are that local expansions of the cultivated area on set-aside area is preferable to displacement of crops which are compensated for by increased agricultural production abroad and that the full press technology in the oil mill is preferable to solvent extraction. Concerning palm oil, cultivation on peat increases the contribution to global warming significantly with a factor of 4–5 compared to cultivation on the current mix of soils types. The other hotspot related to global warming (effluent treatment) can be markedly reduced by installation of digester tanks and subsequent utilisation of biogas.

Conclusions The results of the scenarios show that the approach to system delimitation matters. When the consequential approach to system delimitation is applied in the agricultural stage, uncertainties show to be significant. These uncertainties are mainly related to the determination of how increased production is achieved, increased cultivated area and/or increased intensification. Overall, palm oil tends to be environmentally preferable to rapeseed oil within all impact categories except global warming, biodiversity and ecotoxicity where the difference is less

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pronounced and where it is highly dependent on the assumptions regarding system delimitation in the agricultural stage.

Recommendations and perspectives Since the environmental performance of rapeseed oil and palm oil is a result of the current applied technologies and since improvement options exist in both product systems, it may be more relevant for decision makers to focus on requirements on the applied technologies in the product systems rather than preferring the one oil over the other.

Keywords Agriculture · Consequential modelling · Life cycle assessment · Marginal data · Palm oil · Rapeseed oil · System expansion

1 Introduction

The environmental effect of global versus local supply of products has been broadly discussed in the last decades. An important aspect of the problem is described in the European Environmental Agency's third assessment of Europe's Environment where it is concluded that increasing import of resources to the EU is resulting in a shift of the environmental burden from inside the EU to outside the EU (EEA 2003). A commodity that is associated with those problems of globalisation is vegetable oil. The demand for vegetable oils in the European Union has been increasing by 0.6 million tonnes annually from 1990 to 2004, and since the mid 1990s, the European production has stabilised on around 17 million tonnes/year, whilst the import share has increased from 11% in 1990–1996 to 23% in 2002–2004 (Oil World 2005). Rapeseed oil and palm oil are the most important oils concerning supply to the EU. In 2004, the total demand was 18.3 million tonnes, whereof rapeseed comprised 26% and palm oil 21% (Oil World 2005). There are no indications that the rate with which demand increases should decrease within the years to come. On the contrary, the increased focus on biodiesel will accelerate the demand further (Oil World 2005).

This article compares local and global supply of vegetable oil to the EU. Of the European (EU25) supply in 2004, only 0.9% rapeseed oil was imported, whilst 100% of the supply of palm oil was imported. Thus, rapeseed oil represents the local oil, whilst palm oil represents the global oil. This article presents a life cycle assessment (LCA) of supply of palm oil from Malaysia/Indonesia and rapeseed oil from Denmark to the European market. Vegetable oils are chosen as case because substitutable local and global alternatives exist, because they are highly traded globally, and because they belong to product groups that contribute significantly to the total environmental impact related to EU's consumption, as well as they have high environmental impacts per euro (Tukker et al. 2006).

2 Purpose of the study

This study presents a comparative LCA of the supply of vegetable oil to the European market. Rapeseed oil from Denmark is compared with palm oil from Malaysia/Indonesia. Denmark only represents 2.5% of the total supply of rapeseed in the EU, whilst Malaysia and Indonesia represent 81% of the global supply of fresh fruit bunches (FFB) in 2005 (Schmidt 2007b). Thus, it could be questioned if Denmark is a good representative of the EU supply of rapeseed. For the parameters annual yield, share of total agricultural land covered with rapeseed and fertiliser application, Denmark is very close to the largest suppliers (Schmidt 2007a, p 50; Schmidt 2007b, p 14). Therefore, it is argued that Danish rapeseed production is a good representative of EU rapeseed production. Little knowledge exists on the environmental impacts from local versus global alternatives for supply of products to the EU; examples are Schlich and Fleissner (2005), Weidema et al. (2005), Mattson et al. (2000) and Peters and Hertwich (2006). The cited studies are further debated in Schmidt (2007b, p 5). In addition, very few regulatory and voluntary initiatives ensuring acceptable environmental management upstream in the commodity chain for EU supply of food have been put forward among the key actors. Thus, the intended purposes of this study are to contribute to the knowledge on environmental impacts from local versus global supply and to provide decision support in future governance of the commodity chains of vegetable oils. The LCA is mainly based on data from 2005. The time frame for which the results are regarded as being valid is assessed to be within 5 to 10 years after 2005. The main source of uncertainty in this respect is the change of market trends which will affect the system boundaries. The market trends have been determined using agricultural outlooks for 2005 to 2015 (see Section 4.2).

2.1 Functional unit

The functional unit is defined as 1 t refined vegetable oil suitable for the most important food purposes delivered in Amsterdam. Netherlands is the country in the EU that has the largest imports of palm oil (Oil World 2005). The most important uses of vegetable oils are margarine, shortening, frying fat and salad oil (Bockisch 1998). According to Schmidt and Weidema (2008), rapeseed oil and palm oil are used and substitutable for most food purposes. The compared alternatives for meeting changes in the demand for vegetable oils in the EU are the production of rapeseed oil in Denmark and palm oil in Malaysia and Indonesia.

3 Materials and methods

The general framework for conducting an LCA is found in the ISO 14040 and 14044 standards which are followed in this study (ISO 2006a, b).

3.1 Consequential system delimitation

The consequential approach to system delimitation has been applied, i.e. the system inventoried reflects the actually affected processes (Ekvall and Weidema 2004). The core differences between consequential LCAs and so-called attributional LCAs are that (1) consequential LCA includes the suppliers actually affected by a change in demand instead of averages as in attributional LCA and (2) co-product allocation is avoided by system expansion instead of applying allocation factors (Weidema 2003). A marginal supplier is defined as the one actually affected by a change in demand, and it is identified as the one most sensitive to changes in demand. When the relevant suppliers or technologies are identified, the marginal one can be identified as the most competitive in situations with an increasing or constant market trend and reversely the least competitive in situations with a decreasing market trend. The most or least competitive supplier can be determined on the basis of the price relations between the technologies. Alternatively, it can be assumed that the most competitive suppliers are those which are increasing with the highest rates (historically or predicted). The main argument for applying the consequential approach is that only the actual affected processes are included (Weidema 2003). Suppliers that are not likely to respond to a change in demand should not be included in an LCA since this will not reflect the actual change in environmental impact.

System delimitation in the agricultural stage Some, until recently, blind spots in agricultural LCAs are (1) the identification of the marginal/actually affected crops and regions, (2) the identification of how increased demand for an agricultural product is met and (3) avoided environmental interventions from transformation of non-productive land into agricultural land (Schmidt 2008a). Relating to (1), increased demand for rapeseed in the EU may lead to either increased import or increased cultivation or a combination. If cultivation is increased, it is important to clarify if this affects the area cultivated with other crops in the region. For example, in Denmark where the total agricultural area has been declining in the last decades, it is likely that increased cultivation of rapeseed will cause less area available for other crops. Thus, the marginal crop will be displaced. If it is assumed that increased production of rapeseed does not affect the overall food security in the world, the displaced crop will be compensated for in the region representing the marginal supplier of that crop. Relating to (2), it is relevant to clarify if increased agricultural production is met by increased yield or by increased area, i.e. transformation of non-productive land into agricultural land. This may include intermediate crop displacement; e.g. increased rapeseed in Denmark displaces barley; this 'missing' barley may be produced in Canada either by intensification or by expanding the agricultural land. According to Schmidt (2008a), the difference in environmental impact between these two strategies are significant; increased cultivated area has land use effects, whilst increased yields may have more pronounced effects relating to global warming and eutrophication. Relating to (3), it is well known that even pristine nature causes undesirable emissions, though the level is commonly significantly lower than the emission level from agricultural fields (Werner et al. 2006; Stehfest and Bouwman 2006). Thus, the interventions from cultivation of crops should be represented by the difference between the actual interventions from the arable field and the interventions from the alternative land use, i.e. commonly land under natural vegetation. All identified existing agricultural LCAs only take the interventions from the field into account.

System delimitation in the oil mill stage There are two main product outputs from the oil mill stage: vegetable oil and oil meal which is used for animal fodder. The meal has two functions as animal fodder: protein source and energy source. Thus, when inventorying the interventions relating to the oil, it must be taken into account that the meal substitutes the marginal sources of fodder protein and fodder energy. A method for avoiding co-product allocation by system expansion that takes these factors into account is presented in Schmidt and Weidema (2008).

3.2 Data collection

The data collection is comprehensively described in Schmidt (2007a) which is an inventory report documenting the data collection and system modelling used in this article. The data collection for rapeseed cultivation in Denmark takes its point of departure in cultivation guidelines for rapeseed oil (Dansk Landbrugsrådgivning 2005) and the LCAfood database and its background material (Nielsen et al. 2005; Dalgaard 2007). Emissions from the field in the agricultural stage for all crops are determined by the establishment of nutrient balances and by the use of models for the emissions of N_2O, NO, NH_3, N_2, NO_3, P and for CO_2 from the mineralisation of peat. The most important models are described in IPCC (2000, 2003), FAO and IFA (2001) and Vinther and Hansen (2004). Schmidt (2007a, pp 66–76 and 93–111) presents comparative

information on emission levels when different models and references are available. Data on pesticides in rapeseed cultivation are obtained from Dalgaard (2007), and data for oil palm cultivation are from Singh (2006). The life cycle inventory for the oil and refinery stages for rapeseed oil takes its point of departure in a detailed data collection at AarhusKarlshamns in Aarhus (Korning 2006; Kronborg 2006; Hansen 2006; Aarhus United 2005a, b). The data collection for oil palm cultivation as well as the oil mill and refinery stages takes its point of departure in a detailed data collection for palm oil at United Plantations in Malaysia (Bek-Nielsen 2007; Singh 2006; UPRD 2004). Other important data sources regarding palm oil are the Malaysian Palm Oil Board (Subramaniam 2006a, b; Subramaniam et al. 2004, 2005) and various oil palm research, e.g. Corley and Tinker (2003).

3.3 Method applied for LCIA

The Danish EDIP97 method (Wenzel et al. 1997; Hauschild and Wenzel 1998) has been used. The EDIP methodology has been launched in a revised EDIP2003 version (Hauschild and Potting 2005), but since this revised version was not implemented in the used PC tool (SimaPro) at the time of the study, it was decided to use the well-documented and familiar EDIP97 method. The EDIP method includes toxicities as impact categories, but due to general uncertainties regarding toxicity (Schmidt 2007a), this is not included. The method also includes resource use and waste. These impact categories have been omitted as well. As a sensitivity analysis, the characterised results have been compared with other methods, i.e. Impact 2002+ (Jolliet et al. 2003) and EcoIndicator (Goedkoop and Spriensma 2001). The EDIP97 method in SimaPro is manually updated to a version 2007 (LCA-Center 2007). In addition to the impact categories in EDIP97, land use impacts are also included. Two types of indicators are used to describe this: occupation of land (in terms of hectare years, ha y) and an indicator for biodiversity (related to occupation as well as transformation of land). The life cycle impact assessment (LCIA) method for biodiversity is described in Schmidt (2008b). It should be noted that the applied LCIA method for land use and biodiversity only includes impacts related to occupation and transformation of land and not impacts caused by fertilisers, pesticide and use of machines.

4 System delimitation and presentation of the system inventoried

The production of rapeseed oil and palm oil are divided into three stages: agricultural stage, oil mill and refinery stage and transport stage (from production to destination of use). The LCA includes direct affected processes, overhead (operation of buildings, administration, marketing, etc.) and capital goods (building, machinery and means of transportation). The system delimitation and inventoried scenarios are comprehensively described in Schmidt (2007a).

4.1 Marginal suppliers of affected crops

The system expansions required, as described in Section 3.1, imply that more crops than rapeseed and FFB (oil palm fruit) are affected. Besides vegetable oil, there are co-products from oil milling and refining processes. These are oil meals from the oil mill and free fatty acids from the neutralisation process in the oil refining which substitute the marginal sources of fodder, i.e. soybean meal as the marginal source of fodder protein and barley as the marginal source of fodder energy (Schmidt 2007a). According to Schmidt (2007a), the marginal suppliers of soybean meal and barley are Brazil and Canada, respectively. When soybean meal is displaced, the output of the dependant co-product soybean oil is also affected. Market responses to that will most likely be a change in the production of the marginal vegetable oil, i.e. palm oil from Malaysia and Indonesia (Schmidt and Weidema 2008).

4.2 System expansion in oil mill stage and refinery stage

The method for treating co-products from the vegetable oil product system has previously been dealt with and described in Weidema (1999), Dalgaard et al. (2008) and Schmidt and Weidema (2008). The method in Schmidt and Weidema (2008) is directly applied in this study. The product flows related to production of rapeseed oil (RSO), palm oil and palm kernel oil (PO+PKO), soybean meal and barley are shown in Figs. 1 and 2. According to Schmidt and Weidema (2008), palm oil and palm kernel oil should be considered as one oil output because they are substitutable within many applications. The bottom line in the figures shows the product output for each product system. The product flows and the system expansion are documented in detail in Schmidt (2007a). For the palm oil system, the by-products of mesocarp fibre, empty fruit bunches and shells from the palm oil mill are accounted for by system expansion, but they are not shown in Fig. 1; see Schmidt (2007a) for a detailed description.

Carrying out the system expansion shows that increased demand for 1 t palm oil requires production of 1.001 t palm oil and the displacement of 2.45 kg soybean meal and 198 kg barley (Schmidt 2007a). The additional 0.001 t PO equals the displaced soybean oil which is co-produced with the 2.45 kg displaced soy meal. Correspondingly, increased demand for 1 t rapeseed oil requires the production of the

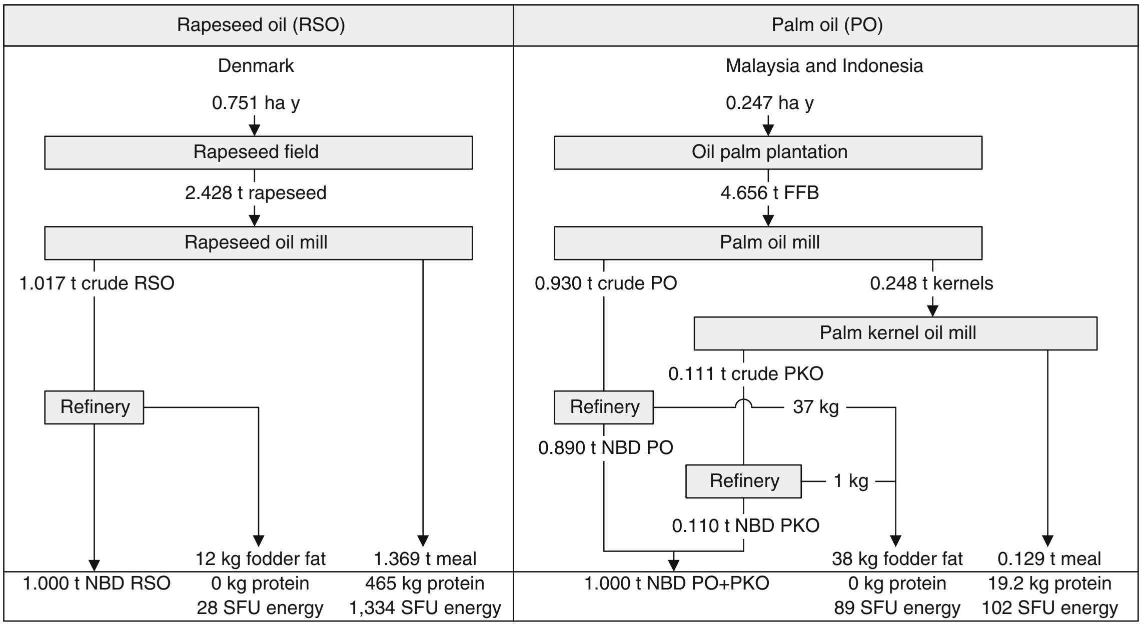

Fig. 1 Product systems and their co-products for the directly affected systems (rapeseed oil and palm oil; Schmidt 2007a). The *bottom of the figure* shows the outputs in terms of oil, fodder protein and fodder energy. *PKO* palm kernel oil, *NBD* neutralised, bleached, deodorised, *SFU* Scandinavian fodder units

1 t rapeseed oil and the displacement of 1.045 t soybean meal and 157 kg barley, whilst additional 255 kg palm oil is required.

System expansion in the agricultural stage In the following, the changes in demand for the required crops described in Section 4.2 will be described regarding system expansion in the agricultural stage, i.e. identification of how increased production is achieved (yield or area) and identification of land constraints and its consequences for the actual affected crops. The description is based on the methodology presented in Schmidt (2008a). The description in this section serves as a basis for the definition of scenarios in

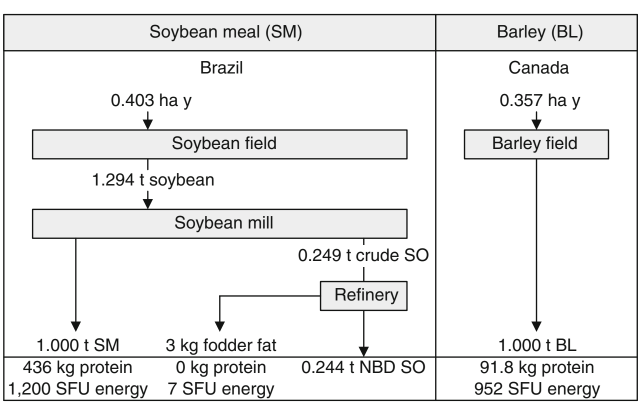

Fig. 2 Product systems and their co-products for the indirectly affected systems (soybean meal and barley; Schmidt 2007a). The *bottom of the figure* shows the outputs in terms of oil, fodder protein and fodder energy. *SO* soybean oil, *SFU* Scandinavian fodder units

Section 4.3. The effects of land transformation are treated separately in a subsection in Section 5.2. This section provides information on the assumed types of land which are transformed into agricultural land.

The change in demand for rapeseed in Denmark can be met either by increasing the yield or by increasing the area cultivated or a combination. If the area cultivated is increased, there are arguments both for and against the fact that this would be likely to affect the total cultivated area in Denmark. An argument which supports that the total cultivated area will increase as a consequence of increased demand for rapeseed is the EU strategy on biofuel (The European Commission 2006a). The European Commission specifies that set-aside areas can be grown with energy crops in order to help further facilitating energy crops. According to The European Commission (2006b) 8,500 km^2 set-aside areas in the European Union have already been used for growing oilseeds for energy purposes. For comparison, the total cultivated area with rapeseed in 2005 in EU25 is 47,600 km^2 (FAOSTAT 2006). On the other hand, an argument against that increased demand for rapeseed will affect the total cultivated area is that the total agricultural area in Denmark has been slightly decreasing in the last decades (Danmarks Statistik 2006), and in addition, a main goal in the Danish forestry action plan is to double the forest area within the next 80 years (The Danish Government 2002). This will increase the total forested area in Denmark from 12% (FAO 2006) to 20–25% (The Danish Government 2002). For comparison, the set-aside area in 2005 covered only 4% of the total area in Denmark (Danmarks Statistik 2006). Thus,

even when including set-aside areas in agricultural production, the agricultural area in Denmark is likely to continue its decrease. Increased area cultivated with rapeseed in Denmark will therefore be likely to displace the marginal crop in Denmark. Schmidt (2008a) has identified the marginal crop in Denmark to be spring barley. The marginal supplier of barley is previously identified as Canada. Thus, the displaced barley in Denmark will be compensated for by increased production in Canada. Based on predictions in FAPRI (2006) on the development of cultivated land and yields the next decade, it can be presumed that 40% of the increase in Danish rapeseed production is met by local increased yields, whilst the remaining 60% is met by increased area which displaces spring barley (Schmidt 2007a).

The amount of displaced spring barley in Denmark is determined by comparing with the yield of rapeseed. From predictions in FAPRI (2006), it can be found that 31% of the future increase in production of barley in Canada is met by yield, whilst the remaining 69% is met by increased area. But increases in the agricultural area in Canada are not regarded as likely since the agricultural area has been almost constant in the last decade. According to FAOSTAT (2006) and FAPRI (2006), the average annual increases in cereal production have taken place and are predicted to take place by 80–90% increases in yields and only 10–20% increases in area. Based on that, increases in the production of cereals are assumed to be achieved by increases in yields only. However, in some of the included scenarios, increases in the production of barley are assumed to be achieved by an increase in the cultivated area. In these cases, it is assumed that the transformed land is prairie grassland in Canada.

If the purpose of the LCA is to compare rapeseed oil from the EU instead of Danish rapeseed oil with palm oil, it could be argued that the increased demand for rapeseed oil produced in the EU would be met by yield and area increases within the EU, i.e. no displacement of other crops in the EU. The reason for this is that the total cultivated area in the EU is predicted to increase (based on FAPRI 2006). In addition, EU is the region in the world that is predicted to face the largest annual increase in rapeseed production the next decade (FAPRI 2006). Therefore, a scenario where increased demand for 1 kg rapeseed is met by 40% increased yield and 60% increased area in the EU (set-aside land) is included. Since the aim of this scenario is to assess the differences between local expansion and abroad expansion of the agricultural area, it is in practice defined as the increases in yield and area taking place in Denmark, i.e. data for Danish yield and Danish technology is applied.

The change in demand for FFB in Malaysia and Indonesia is assumed to take place by 4% increased yield and 96% increased area. Since it has not been possible to identify any data on predicted yields and cultivated area for the future, the distribution between yield and area is based on historical data from FAOSTAT (2006) from 1995 to 2005. The change in demand for soybean in Brazil is presumed to take place by 19% increased yield and 81% increased area. This presumption is based on predictions for the next decade in FAPRI (2006). When inventorying FFB production, it is assumed that replanting of oil palms is done without burning the biomass residues. Figures 3 and 4 summarise the affected processes when performing system expansion in the agricultural stage.

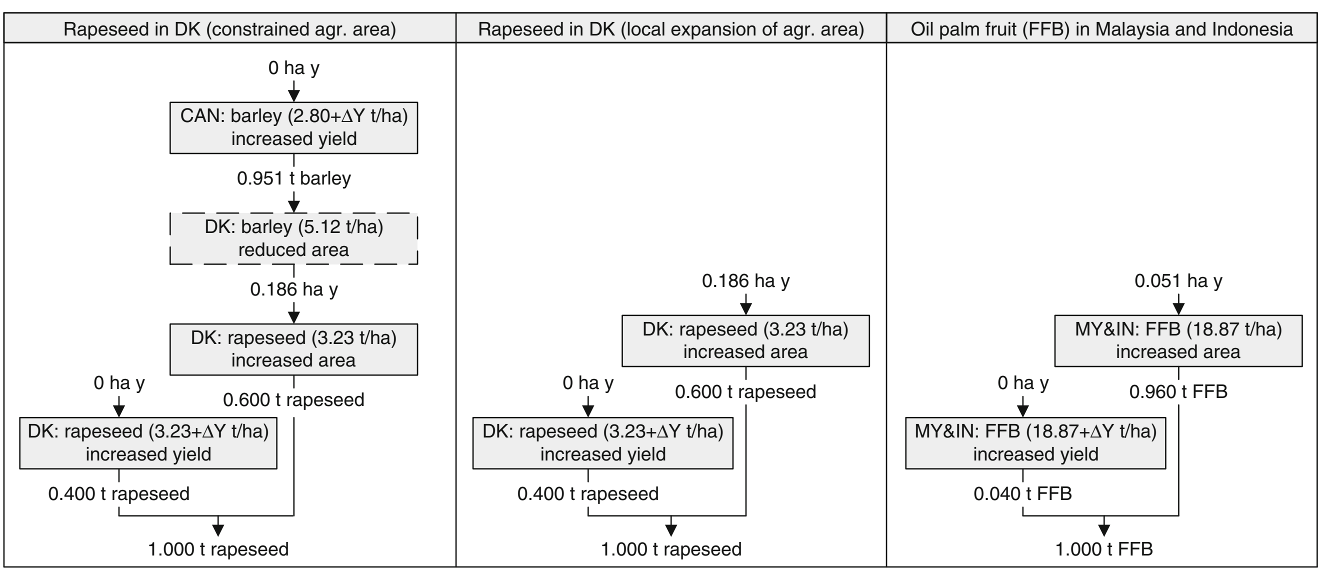

Fig. 3 Expanded agricultural product systems related to 1 t rapeseed and 1 t FFB. *CAN* Canada, *DK* Denmark, *MY&IN* Malaysia and Indonesia. Δ*Y* represents the desired increase in yields when increased production is achieved that way

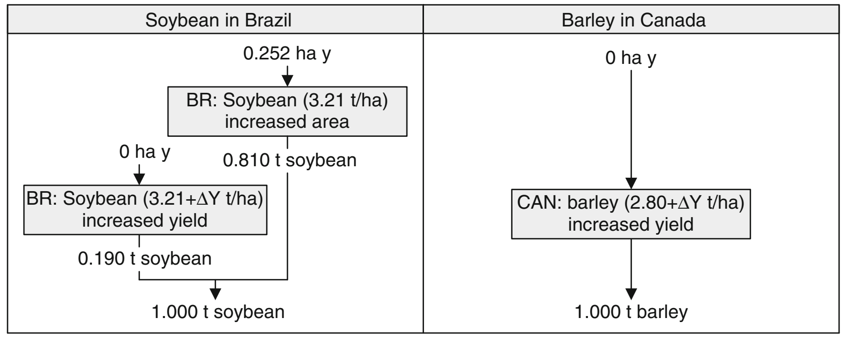

Fig. 4 Expanded agricultural product systems related to 1 t soybean and 1 t barley. *CAN* Canada, *BR* Brazil. Δ*Y* represents the desired increase in yields when increased production is achieved that way

4.3 Scenarios inventoried

Most LCAs on products from oil crops are performed using the traditional approach to system delimitation, i.e. allocation is typically done by economic value, by energy content or by mass, and system expansion is not taken into account (Defra 2005; Beer et al. 2002; Mehlin et al. 2003; Wightman et al. 1999; McManus et al. 2004; Yusoff and Hansen 2007; Zah and Hischier 2003; Koch 2003). Some LCAs on oil crop products have adopted consequential modelling in the oil mill stage (Dalgaard et al. 2008; Nielsen et al. 2005; Gärtner et al. 2006; Weidema and Wesnæs 2006). However, no existing LCAs which include system expansion in the agricultural stage have been identified.

In order to make the results of the present LCA as transparent and comparable with other LCAs as possible, the results are shown on all three levels of life cycle inventory modelling. Scenarios 1–3: consequential modelling (system expansion in the oil mill stage as well as in the agricultural stage), scenario 4: semi-consequential modelling (only taking system expansion in the oil mill stage into account) and scenario 5: attributional modelling (no system expansion). Scenarios 4 and 5 are only included for the purposes of comparing with other LCAs. The economic allocation factors applied in the attributional modelling are based on the product flows shown in Fig. 1 and the average prices on oils and meals from 1996/1997 to 2003/2004 provided in Oil World (2005). For rapeseed milling, the allocation factors are 73% for the oil and 27% for the meal, and for FFB and palm kernel milling, the allocation factors are 98% for the oil and 2% for the meal. From 1996/1997 to 2003/2004, the relative world market prices on oils and meals have been changing so that the allocation factor for palm oil would vary from 97.5% to 98.7% and the allocation factor for rapeseed oil would vary from 66% to 78%. Table 1 provides an overview of the different alternative scenarios of the product systems that are included in the study.

5 Impact assessment results

5.1 Characterised results

Table 2 shows the characterised results for the five scenarios.

It appears from Table 2 that the results obtained from the different scenarios differ significantly. For example, 1 t rapeseed oil causes between 2.22 and 17.1 t CO_2-eq. and is associated with land use occupation between −0.28 and 0.96 ha y. Hence, it is clear that the way to achieve changes

Table 1 Overview of the included scenarios relating to system delimitation

Scenarios: compositions of product systems	Description of product system	
	1t rapeseed oil in Denmark	1t palm oil in Malaysia and Indonesia
Sc (1): Consequential modelling in oil mill and agr. stages. Marginal increases are assumed to be achieved by a combination of increase in agr. area and yields	(a) RSO (constrained area) and (b) RSO (local expansion)	PO+PKO
Sc (2): Consequential modelling (area only) in oil mill and agr. stages. Marginal increases are assumed to be achieved by increase in agr. area only	(a) RSO (constrained area) and (b) RSO (local expansion)	PO+PKO
Sc (3): Consequential modelling (yield only) in oil mill and agr. stages. Marginal increases are assumed to be achieved by increase in agr. yields only	RSO	PO+PKO
Sc (4): Semi-consequential modelling, system expansion in oil mill stage and attributional modelling in agr. stage	RSO	PO+PKO
Sc (5): Attributional modelling, i.e. economic allocation and no system expansion	RSO (73% allocated to oil)	PO+PKO (98% allocated to oil)

Table 2 Characterised results of the five scenarios

Impact category	Scenario 1			Scenario 2			Scenario 3		Scenario 4		Scenario 5	
	RSOa	RSOb	PO	RSOa	RSOb	PO	RSO	PO	RSO	PO	RSO	PO
Impacts from continuously cultivation/land occupation												
Global warming (t CO_2)	12.0	8.19	2.16	5.15	2.40	2.32	17.1	2.60	2.39	2.36	2.22	2.47
Ozone depletion (mg CFC11)	366	304	43.8	210	147	44.6	549	77.8	147	44.6	163	54.5
Acidification (kg SO_2)	52.2	47.9	13.8	39.2	25.8	13.0	82.4	23.5	26.0	13.3	20.2	14.8
Eutrophication (t NO_3)	1549	1159	80.6	201	172	102	2733	337	211	119	140	124
Photochemical smog (kg ethene)	1.36	1.30	0.526	1.22	0.869	0.509	1.95	0.617	0.869	0.509	0.887	0.551
Land use (ha y)	−0.281	0.170	0.235	0.960	0.337	0.175	0	0	0.337	0.175	0.548	0.242
Biodiversity (wS100)	1.12	16.9	6.64	2.37	27.3	6.84	0	0	27.3	6.84	19.2	6.78
Impacts from land transformation												
Land transformation (m^3)	−28.1	17.0	23.5	96.0	33.7	17.5	0	0	33.7	17.5	54.8	24.2
Global warming (t CO_2)	−0.874	−0.446	0.952	0.0611	−0.462	0.931	0	0	−0.462	0.931	0.521	0.978
Biodiversity (wS100)	−2.95	−2.53	0.560	15.3	−3.77	−0.426	0	0	−3.77	−0.426	0.516	0.588
Sum of occupation and transformation impacts												
Global warming (t CO_2)	11.1	7.74	3.11	5.21	1.94	3.25	17.1	2.60	1.93	3.29	2.74	3.45
Biodiversity (wS100)	−1.83	14.4	7.20	17.7	23.5	6.41	0	0	23.5	6.41	19.7	7.37

in cultivation matters. It must be stressed that the results of scenarios 1 and 3 are more uncertain than the other scenarios. The reasons for this are uncertainties in identifying the marginal means of increasing yields and determining crop responses to additional fertiliser input (see Section 6.2). The underlying reasons for the differences in the scenarios are explained further in Section 5.2. Comparing across the scenarios, palm oil falls out to be the environmentally preferable alternative within the impact categories: ozone depletion, acidification, eutrophication and photochemical smog. For global warming, land use and biodiversity, the picture is less clear. Here, two factors determine the result, i.e. (1) how are changes in cultivation achieved and (2) what is the distribution between changes achieved by area and by yield? Except from land use, the largest impacts for rapeseed oil as well as palm oil are found in scenario 3 where increased cultivation is met by increased yields. For rapeseed oil, also scenario 2a, where changes in demand are met by displacement of crops (displaced barley in Denmark is compensated for by increased cultivation in Canada), shows large impacts.

5.2 Process contribution

Normalising and weighting the characterised results using EDIP97, Impact 2002+ and EcoIndicator point at different impact categories is the most significant. Therefore, this approach for identifying the most significant impact categories is not regarded as useful. Instead, global warming, land use and biodiversity are focused on. Firstly, land use and biodiversity are normally not well covered in LCA studies, but in policy documents and NGO campaigns, these impacts have a major role. Secondly, global warming has been chosen because it occupies a still larger part of the environmental agenda. In addition to these impact categories, attention is given to ecotoxicity later in this section. Figure 5 shows the contribution to global warming, land use and biodiversity from different processes.

Global warming It appears from Fig. 5 that the most significant contributions to global warming from rapeseed oil come from cultivation of rapeseed in Denmark, displaced soybean cultivation in Brazil (negative) and, in some scenarios, cultivation of barley in Canada. The oil mill and refinery process as well as transportation of rapeseed oil from Denmark to Amsterdam fall out to be less significant. The relevant emissions contributing to the significant processes are shown in the following: rapeseed cultivation in Denmark (66% N_2O, 33% CO_2 and 1% other), soybean cultivation in Brazil (61% N_2O, 37% CO_2 and 2% other) and barley cultivation in Canada (44% N_2O, 54% CO_2 and 2% other). Nitrous oxide mainly comes from field emissions (denitrification and nitrification) and from

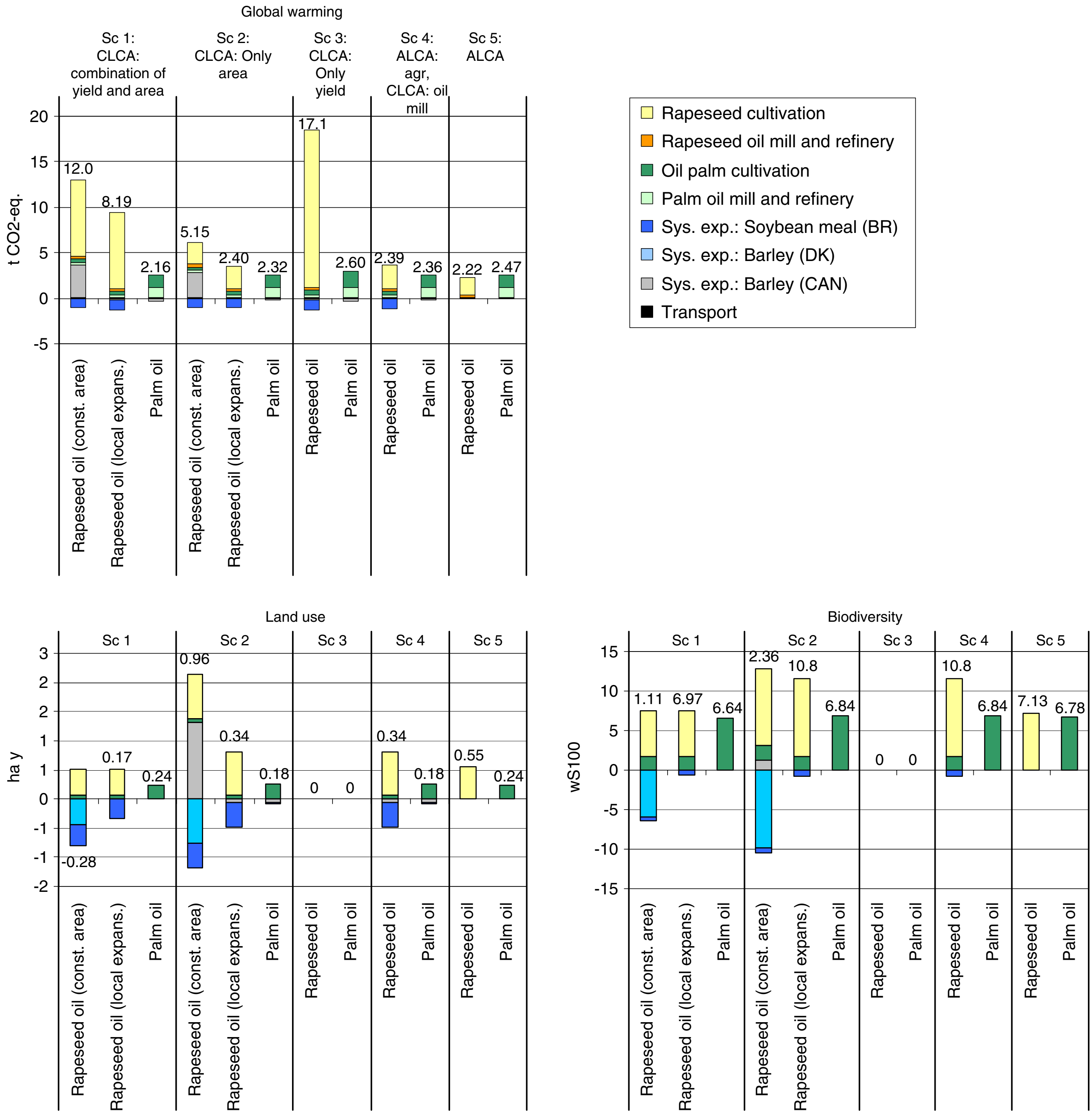

Fig. 5 Process contribution to global warming, land use (occupation) and biodiversity (occupation). Characterised results of the five scenarios. The five scenarios are described in Table 1. *CLCA* consequential LCA, *ALCA* attributional LCA, *BR* Brazil, *DK* Denmark, *CAN* Canada

production of N fertiliser. Carbon dioxide comes from production of fertiliser, traction and from transportation of agricultural inputs. The relatively large contributions to global warming in scenarios 1 and 3 can mainly be explained by inefficient marginal yield increases by additional N fertiliser in Denmark. But also crop displacement between rapeseed and barley in Denmark (only in the constrained area versions of scenarios 1 and 2) contributes significantly to global warming. The reason for this is that displacement of spring barley in Denmark (8 kg CO_2-eq./t) is compensated for by barley in Canada (720–1.650 kg CO_2-eq./t). The displacement of spring barley in Denmark takes place when land is constrained and when changes in cultivation are met by increased cultivated area. The difference between global warming from spring barley in Denmark and barley in Canada is due to the fact that straw is utilised as biofuel for heat and electricity generation in Denmark, whilst it is left in the field in Canada (Schmidt 2007a).

The most significant contributions to global warming from palm oil are from oil palm cultivation (53% N_2O, 46% CO_2 and 1% other) and from the palm oil mill and refinery stage (87% methane, 11% CO_2 and 2% other) where anaerobic digestion of palm oil mill effluent causes significant methane emissions. Nitrous oxide comes from field emissions (denitrification), and CO_2 mainly comes from degradation of cultivated peat, from transportation of palm oil from SE Asia to Amsterdam, production of fertiliser and from energy generation for palm oil refining. It appears that there is only little difference between the contributions to global warming from palm oil in the different scenarios. This is because the amount of other crops affected from palm oil is smaller than from rapeseed oil.

Land use and biodiversity (occupation of land) The impacts related to land use shown in Fig. 5 are related to occupation of land only. Impacts related to transformation are difficult to relate to the functional unit and are dealt with separately in the next section. The most significant contributions to land use and impacts on biodiversity from rapeseed oil production come from rapeseed cultivation in Denmark. However, in the scenarios with constrained land, (scenarios 1a and 2a), the land use and associated impacts on biodiversity from rapeseed cultivation in Denmark are balanced out by displaced spring barley. The corresponding increase in barley production in Canada only appears in scenario 2 because scenario 1 assumes that increases in cereal production are achieved by increased yield alone which shows no effects on land use and biodiversity given the applied LCIA method (Schmidt 2008b). It also appears from Fig. 5 that the land use associated with soybean cultivation in Brazil has insignificant impacts on biodiversity. The reason for this is that occupation of 1 ha in Denmark has a larger impact than occupation of 1 ha in Brazil. The underlying explanation here is that ecosystems in Denmark are more vulnerable to land use processes than in Brazil because a much smaller fraction of Denmark is under natural vegetation/extensively cultivated which means that a smaller fraction is capable of supporting a natural level of species richness (see Section 6.2). The concept of ecosystem vulnerability is further described in Schmidt (2008b).

The impacts on land use and biodiversity from palm oil do not vary significantly in the different scenarios. The main contribution comes from the cultivation of oil palm. In scenarios 2 and 4, the impacts are smaller because the co-product from palm kernel oil milling and oil refining displaces barley produced by increased area in Canada.

Impacts associated with transformation of land The impacts on land use, biodiversity and also global warming, dealt with above, are only those which are associated with occupation/continuous cultivation of land. Especially in the case of SE Asia and South America, the impacts related to transformation of land are often of more concern than those from continuous cultivation. However, these impacts are difficult to relate to the functional unit. Therefore, they are dealt with separately here. A choice has been made not to show the impacts from transformation of land in Fig. 5. This is due to the fact that some additional uncertainties would be added on top of the uncertainties in the inventories of the five scenarios. The main sources of additional uncertainty here is the determination of the land use types that are transformed into agricultural land and the allocation of transformation impacts to the functional unit. Table 3 shows the typical types of land transformed into agricultural land in the relevant regions. It is assumed that transformation of forest into agriculture is from degraded/secondary forest to intensive agriculture. The impact on biodiversity would be significantly higher if primary forests were transformed instead. However, the determining activity in transforming primary forests into degraded/secondary forests is logging. When comparing the disappearance rate of primary forests with the rate of agricultural expansion in Brazil and Indonesia in FAO (2006) and FAOSTAT (2006), it appears that between the years 2000 and 2005, primary forests have been disappearing three to four times faster than the expansion of agricultural land. This indicates that logging is the activity that determines the rate of degradation of primary forests. The inventory data relating to transformation of land are comprehensively described in Schmidt (2007a).

It appears from Table 3 that there are significant differences between the impacts from the transformation of 1 ha for different land use types and regions. It is worth

Table 3 Characterised results of transformation of 1 ha different land use types (based on Schmidt 2007a, 2008b)

Region	Denmark	Malaysia/Indonesia		Brazil		Canada
Transformation from…	Set-aside	Sec. forest	Grassland	Savannah	Sec. forest	Grassland
Transformation to…	Rapeseed	Oil palm	Oil palm	Soybean	Soybean	Barley
Global warming (t CO_2 per ha)	95	437	−33	303	796	90
Biodiversity (wS100 per ha)	94	385	−142	928	538	1,438

noting that transformation of alang-alang grassland into oil palm in Malaysia and Indonesia is associated with negative impacts on global warming and biodiversity. This is because more species are supported and a larger standing stock of carbon is present in oil palm plantations than in alang-alang grassland. It also appears that the magnitude of the impacts is smaller in the case of transformation processes in Denmark than in Malaysia and Indonesia.

In the lower part of Table 2, the impacts related to transformation are shown. It has been assumed that the transformation of land supports cultivation in 100 years. It is obvious that this assumption is related to significant uncertainties, both as uncertainties of the 100 years and of differences between different regions. The impacts from transformation are calculated using the normalised data in Table 3 and the land use given in Fig. 5. The impacts related to transformation show some surprising results in scenarios 1, 2 and 4; the contributions to global warming and biodiversity from rapeseed oil are negative. The reason for this is that the transformations in Denmark cause relatively small impacts, whilst the avoided impacts on transformation in Brazil and Canada have larger magnitudes. Also, biodiversity related to palm in scenarios 2 and 4 shows negative impacts. The reason for this is that the biodiversity impact from avoided barley in Canada is weighted relatively high because untouched nature (prairie grassland) is affected. However, it is difficult to say how much of this avoided barley will actually be cultivated by expanding agricultural land on primary prairie grassland. There may also be some degraded land available for agricultural expansion of barley which would reduce the weighting of avoided barley production.

Looking at only the required land for production of 1 t rapeseed oil and 1 t palm oil as shown in Fig. 1 (and hence no system expansions) and assuming set-aside land being transformed in Denmark and 50% alang-alang grassland and 50% degraded forest being transformed in Malaysia and Indonesia, the impact would be that 1 t rapeseed oil would require 0.00751 ha which causes the impacts 0.71 t CO_2-eq. and 0.71 wS100, whilst 1 t palm oil would require 0.00247 ha and causes impacts 0.50 t CO_2-eq. and 0.30 wS100. It appears that the impact from rapeseed oil is more significant than from palm oil. However, the results for palm oil are very sensitive to the distribution between transformed alang-alang grassland and forest into oil palm. If degraded/secondary forest (and no alang-alang land) were transformed into oil palm, 1 t palm oil would cause 1.08 t CO_2-eq. and 0.95 wS100, and if the transformed forest was primary forest, the impact on biodiversity would be as high as 17 wS100 (Schmidt 2008b). Comparing the impacts on transformation with the characterised results for occupation in Table 2, it appears that the impacts from the transformation processes cannot be ignored. Especially, the transformation impacts on biodiversity from rapeseed oil (constrained area) are significant. This is because of the high weighting of nature in Canada. Generally, the contribution to global warming from transformation from rapeseed oil is not significant, but for palm oil, the contribution from transformation corresponds to a little less than 50% of the contribution from occupation, which is indeed significant.

Ecotoxicity In general, existing LCIA methods are associated with considerable uncertainties regarding toxicity. For example, if calculating the characterised results of aquatic ecotoxicity associated with palm oil in scenario 1 using EDIP97, Eco-indicator (H) and Impact2002+, the intersection of top five of the contributing emissions for the three methods are zero and the total number of emissions present are 13 out of 15 possible. Thus, existing LCIA methods on ecotoxicity provide little help in assessing the impacts on ecotoxicity. However, most of the contributing emissions identified in the aforementioned analysis are pesticides (mainly cypermethrin and chlorpyrifos) and heavy metals from fertilisers (mainly copper, zinc, chromium and nickel). Regarding pesticides, rapeseed oil seems to be preferable to palm oil since the use of pesticides in rapeseed cultivation is relatively low and at the same time the use of pesticides in avoided soybean cultivation is relatively high. On the other hand, more fertilisers are used in rapeseed cultivation, which indicates that ecotoxicity related to heavy metals is more significant from rapeseed oil than palm oil.

6 Discussion

6.1 Comparison of palm oil and rapeseed oil

As described in Section 5.1, palm oil performs better than rapeseed oil for the impact categories ozone depletion, acidification, eutrophication and photochemical smog. For the remaining impact categories, the result depends on assumptions regarding system delimitation. For global warming, palm oil is preferable to rapeseed oil if increases in production are achieved by increased yield (scenarios 1 and 3). If increases in production are achieved by increased area (scenario 2) and if more traditional approaches to system delimitation are applied as in scenarios 4 and 5 (i.e. no considerations on how increased production is achieved), the differences are insignificant, except in the case where constrained area is supposed for rapeseed oil which is significantly higher than palm oil. If the figures for transformation impacts are added on top of the impacts relating to continuously cultivation (see lowest part of Table 2), this will be in favour of rapeseed oil. But it must be stressed that the figures relating to land transformation in

Table 2 are very sensitive to the assumed allocation of the transformation to the functional unit and the type of land affected.

For land use (occupation, ha y), palm oil is performing better than rapeseed oil except if the expected changes in yields and cultivated area are taken into account (scenario 1). In that case, the product system of rapeseed oil seems more likely to change its production by increasing yields than the product system of palm oil. For biodiversity (from occupation of land), the picture is less clear. If increased production of rapeseed oil is achieved by cultivation of set-aside areas (local expansion) in Denmark, the impact on biodiversity seems to be larger than from palm oil. However, if rapeseed cultivation is increased at the expense of spring barley, which is then compensated for by increased spring barley in Canada, rapeseed oil seems to perform better than palm oil. This is mainly because biodiversity in Denmark is more vulnerable to occupation processes than in more extensively cultivated regions of the world. When the figures for transformation impacts are added on top of the impacts relating to continuously cultivation (see lowest part of Table 2), the ranking of palm oil and rapeseed oil is changed for scenario 2 where palm oil is now the best performing oil. The reason that rapeseed oil (constrained area) is associated with high transformation impacts is that the transformation of prairie grassland in Canada is weighted relatively high.

It is not possible to give a straight answer to which oil is the environmentally preferable. It depends on how increased production is achieved (area or yield), uncertainties related to transformation impacts and on the nature of market mechanisms (illustrated by different scenarios representing different market responses to increased demand). Therefore, it is interesting to identify which cultivation practices and production technologies are environmentally preferable/undesirable and if some of those make the difference between rapeseed oil and palm oil more significant. This is dealt with in the next section.

6.2 Uncertainties

Contribution to global warming from palm oil is higher than found in other studies The contribution to global warming per 1 t palm oil in this study is significantly higher than in some other studies identified: 0.64 t CO_2-eq./t palm oil (Yusoff and Hansen 2007) and 0.74 t CO_2-eq./t palm oil (Zah and Hischier 2003; ecoinvent 2004). The main reasons for this difference are (1) this study includes N_2O from N surplus during replanting (an N balance has been established for each of the 25 years of the plantation life cycle), and (2) this study includes CO_2 emission from cultivation on peat soils. Another study (Gärtner et al. 2006) shows 1.6–2.4 t CO_2-eq. per tonne palm oil, which is in better accordance with this study. Comparing with the mentioned studies, the data collection in this study is regarded as the most comprehensive and complete.

Palm oil and peat soils In this study, it is assumed that 4.1% of the land cultivated with oil palm is peat. This is based on Henson (2004) which is valid for Malaysia in approximately the year 2000. Today, the area cultivated with peat is higher in Malaysia. No data have been identified for Indonesia. Because of the lack of valid data, the 4.1% has been used. Cultivation on peat increases the contribution to global warming significantly; the CO_2 emission from cultivated peat soils are ~37 t CO_2/ha y, which corresponds to ~10 t CO_2/t crude palm oil (Schmidt 2007a, p 109). A large share of the remaining land available for expansion of oil palm cultivation in SE Asia is peat soil (Corley and Tinker 2003; Wetlands International 2007). Thus, if not avoiding increased cultivation on peat, increase of the production of palm oil in the future will have a significantly higher impact on global warming.

Modelling of increased yield The characterised results of rapeseed oil by increased yield (scenarios 1 and 3) show significantly higher contributions to global warming than the other scenarios. The reason for this is that the level of fertiliser application is already very high, and therefore, the crop response to additional fertiliser is relatively low. However, three things make the modelling uncertain. First of all, the use of fertiliser in Denmark and EU is regulated by maximum N norms (The European Parliament and the Council 2000; The European Council 1991). Secondly, increases in yield will probably take place where the largest crop response is achieved, which will be in fields where the fertiliser application is below average. Thirdly, the marginal way of increasing yields in the EU may be through, e.g. biotechnology and not additional application of fertiliser. Thus, the calculated impacts when modelling rapeseed oil by increased yield in scenarios 1 and 3 are probably overestimated.

Increased yields versus increased area Scenario 1 shows that rapeseed oil performs significantly better than palm oil regarding land use and biodiversity. This is primarily because agricultural statistics and outlooks predict that increases in demand for the product system of rapeseed oil will be more likely to respond by increased yields than the product system of palm oil. However, these predictions are uncertain and the ratio between increases in yield and area is related to the identification of marginal suppliers, which is also related to uncertainties.

Biodiversity The results shown for biodiversity are uncertain in the sense that the indicator on biodiversity is based

on the number of species of vascular plants that are prevented from living in the desired area (weighted for ecosystem vulnerability). Since the LCIA method for biodiversity ascribes the same weight to all species of vascular plants and since the affected land use types in Denmark (agricultural fields and set-aside areas) mainly contain uninteresting common species, the model setup may be in favour of rapeseed oil. In addition, the ecosystem vulnerability is determined on a country basis. Many of the regions where oil palm, soybean and barley are dominant in the landscape are larger than the total area of Denmark. Hence, the low weighting of the ecosystem vulnerability in these regions may be too low compared to Denmark if they are considered to be ecosystems themselves. If the weighting factor for ecosystem vulnerability was the same for all regions, palm oil would have a larger impact on biodiversity than rapeseed oil.

Utilisation of straw The contribution to global warming from rapeseed oil (constraint area) is higher than rapeseed oil (local expansion). Some of this difference is due to different cultivation practises for barley in Denmark and Canada, but some of the difference is also related to the fact that some straw is utilised as biofuel in Denmark, whilst it is not in Canada. The straw utilisation in Denmark is likely to be higher than in the rest of the EU. Therefore, a share of the high contribution from rapeseed oil (constraint area) is specific to Danish conditions and not European conditions.

7 Conclusions

The purpose of the LCA of rapeseed oil and palm oil is to provide environmental information on local supply versus global supply of vegetable oils to the EU. The consequential approach to system delimitation is adopted because the purpose of the LCA is to predict future environmental impacts and to provide information to policy making. However, in order to provide transparency and comparability with previous LCAs within the field, additional scenarios (scenarios 4 and 5) with other system delimitations are also included. It appears that especially when applying the consequential approach in the agricultural stage, the results tend to be uncertain because of difficulties in modelling increased yields and in determining the ratio between increased yields and increased area. Therefore, as also described in Schmidt (2008a), the increased completeness and accuracy in results achieved by adopting the consequential approach is somehow obtained at the expense of a less precise result. The results show that the difference in the contribution to global warming from rapeseed oil and palm oil is limited if increased production is achieved by a change in the cultivated area and if increased rapeseed cultivation is achieved by increased cultivation locally (scenario 2). However, if the uncertain modelling of increased yields of rapeseed is included (scenarios 1 and 3), palm oil showed to perform best. Regarding land use, palm oil causes least occupation of land (scenario 2). But if the predicted uncertain ratios between increases in yield and area are included (scenario 1), the product system of rapeseed tends to respond to changes in demand with a greater share of yield than oil palm, leading to a better performance regarding land use. Comparing the results for rapeseed oil and palm oil regarding biodiversity, the best performing oil is difficult to point out. The impacts on biodiversity are very sensitive to the boundary settings and assumptions on ecosystem vulnerability in the LCIA method. Taking the assumptions and system settings in scenario 2 for good, the ranking is as follows: Rapeseed oil (constrained area) performs the best, palm oil performs second best, and rapeseed oil (local expansion) performs least good. But if the impact on biodiversity from land transformation is also included, palm oil performs the best. However, taking into account that ecosystem vulnerability may be underestimated in Malaysia/Indonesia, Brazil and Canada, the results may change in favour of rapeseed oil. Regarding ecotoxicity, the LCIA methods available are too uncertain to provide sufficient information when comparing the two oils. For the remaining impact categories, palm oil performs better than rapeseed oil. Overall, it is assessed that palm oil most likely is environmentally preferable to rapeseed oil within land use, ozone depletion, acidification, eutrophication and photochemical smog, whilst it is more unclear which oil performs best within global warming, biodiversity and ecotoxicity.

8 Recommendations and perspectives

The results and conclusions presented in this study reflect the currently used technology in the product systems of rapeseed oil and palm oil. Therefore, the results presented are only valid under these circumstances. Improvement options exist in both product systems. Some of the hotspots identified in Section 5 on results are (1) the production of N fertiliser used for rapeseed cultivation, (2) methane emissions from palm oil mill effluent and (3) CO_2 emissions from the cultivation of oil palm on peat soils. Examples of improvement options are: ad. (1) N_2O emissions from N fertiliser production can be almost eliminated (The European Commission 2006c), ad. (2) installation of digester tank for capturing and utilising biogas (CH_4) from palm oil mill effluent treatment (several CDM projects have been initiated) and ad. (3) avoiding cultivation of oil palm on peat soils. It should be noted that the mentioned improvement options are not an exhaustive list of all improvement options. More

improvement options are discussed and analysed in Schmidt (2007a). The examples above illustrates that it may be more relevant for decision makers to focus on requirements on the applied technologies in the product systems rather than preferring the one oil over the other.

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